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ENVIRONMENTAL FEATURES AND BIOTA OF ANCHIALINE POOLS ON CAPE KINAU, MAUI, HAWAII

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SUMMARY

Anchialine pools of Cape Kinau, a 200-year-old lava flow on Maui Island, Hawaii, are described in terms of distribution, basin character, water quality, and aquatic biota. The pools, typically with either rock or sediment basins, occur in groups (12) along 3 km of shoreline. A year-long survey determined that temperatures and salinities varied from 20 to 30.5 °C and 6 to 33.5‰, respectively. Most of this variation occurred daily in response to solar and tidal cycles. More than 140 species of algae were found, the most characteristic and obtrusive growths being extensive crusts and mats formed by filamentous cyanophytes in association with other algae. The fauna, dominated by crustaceans, included a few species each of fishes, mollusks, polychaetes, and other marine-related invertebrates. Decapod crustaceans provided the greatest diversity and abundance of any major faunal group and included five identified species of hypogean shrimps, the largest number known for any single Indo-Pacific location. This unique site is now protected as a State Natural Area Reserve.

RÉSUMÉ

On décrit la distribution, la morphologie, la composition de l'eau et les biotes aquatiques d'habitats anchialins de Cape Kinau (écoulement de lave vieux de 200 ans, Maui, Hawaii). Les "pools" anchialins, remplissant des bassins soit rocheux soit tapissés de sédiments, sont groupés (12 groupes) le long de 3 km de côtes. Mesurées pendant une année, les températures ont varié de 20 à 30,5 °C., les salinités de 6 à 33,5‰; le plus important de ces variations est enregistré pendant la journée, comme réponse aux cycles solaire et tidal. Plus de 140 espèces d'algues ont été identifiées, le développement le plus caractéristique et massif étant celui des croûtes formées par des cyanophycées filamenteuses en association avec d'autres algues. Dominée par les crustacés, la faune comprend aussi quelques espèces de poissons, mollusques, polychètes et autres invertébrés à affinités marines. Le diversité et l'abondance maximum est enregistrée par les décapodes: 5 espèces hypogées déterminées, le plus grand nombre connu pour une localité de l'Indo-Pacifique. Cette localité unique est à présent protégée comme Réservation Naturelle d'Etat.

INTRODUCTION

"State considers Maui Reserve to protect new shrimp species" proclaimed a bold caption in the October 16, 1972 issue of the *Honolulu Advertiser*, a major daily newspaper. The news article went on to explain that the unnamed unique shrimp was one of several crustaceans found in brackish pools on Cape Kinau, Maui, and that it was only one of the reasons why the State was considering natural area reserve status for the area. The featured shrimp, subsequently named *Procaris hawaiana* Holthuis, 1973, was a second species in the family Pro-

caridídae erected by Chace & Manning (1972) for a primitive shrimp discovered on Ascension Island in the South Atlantic Ocean. Continued exploration of Cape Kinau uncovered other rare biota and unusual ecological conditions in the anchialine pools formed within the rugged lava flow.

The anchialine pools of Cape Kinau attracted scientific attention mainly because of unique crustaceans (Holthuis, 1973; Barnard, 1977) and algal communities (Wong, 1975). Of particular note are various hypogean shrimps (five species identified) found in the pools which are surface extensions of subterranean crevicular habitat. The diversity of these shrimp at a single site is the greatest known in the Indo-Pacific and perhaps in the entire world (cf. Iliffe et al., 1983; Maciolek, 1983). Despite the scientific importance of the Cape Kinau pools in terms of taxonomy, zoogeography, and aquatic ecology, no comprehensive description of their environmental character or total biota has been published. It is the purpose of this paper to provide such a description by combining unpublished survey data with published reports on crustaceans and algae noted above.

Various faculty and graduate students of the University of Hawaii assisted in field surveys, identified biota, or provided useful commentary. I especially appreciate identifications of mollusks and polychaetes provided by Drs. E. Alison Kay and Julie Brock, respectively, of the University of Hawaii.

CAPE KINAU

A small coastal prominence on the southwesterly tip of East Maui Island appeared about 1790 at the lower end of a rift zone on the massive Haleakala shield. The approximate date of formation of Cape Kinau was deduced by Oostdam (1965), who compared coastal charts prepared by explorers La Perouse in 1786 (cape not shown) and Vancouver in 1793 (cape indicated). Most of the lava was derived from a single vent, Kalua o lapa, situated at 175 m elevation and 3 km from the present shoreline. This flow covers about 400 ha and consists of raw, dark brown, clinkery lava (a'a). Scarcity of vegetation can be attributed to the high porosity of the lava and the low rainfall (50 cm/yr) of the area.

The lava surface has rugged relief with ridges and tumuli rising several meters above surrounding depressions. The shoreline, about 4 km long, is extremely irregular and nearly devoid of beach sediments. At several places along this shoreline, depressions in the lava extend below sea level resulting in scores of tidally influenced water exposures — anchialine pools which are the focus of this paper.

POOL DISTRIBUTION AND CHARACTER

The term "pool" herein refers to any water exposure within the lava, be it a pond or water visible within fissures, cracks, or dim recesses beneath rock

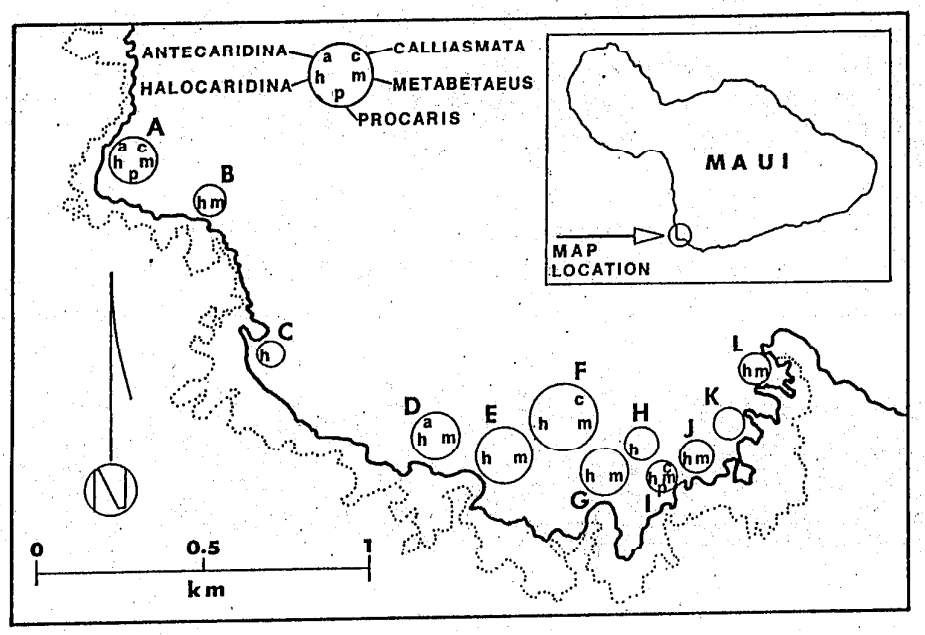

Fig. 1. Cape Kinau, Maui, showing locations of anchialine pool groups (A through L) and the distribution of hypogean shrimps (cf. tables I and III). Circle size is roughly proportional to the water surface area of a pool group. Dotted line is the apparent undersea extension of the 1790 lava flow as determined from aerial stereo photographs.

overhangs. Pools are distributed in groups along 3 km of shoreline as shown in fig. 1. Each of the 12 groups consists of a few to many pools in close proximity, the groups being separated by considerable distance, by lava of high relief, or by a combination of both features. The groups are identified by letter code A through L; table I also lists codings used by Holthuis (1973) and Wong (1975) which refer more to individual pools or pool subsets than they do to the entire complement of pools in a given locality. Holthuis' pools g and v, and Wong's pools C and Q are not indicated inasmuch as they have direct, but restricted, connection to the ocean and therefore are not strictly anchialine.

Individual pools vary in surface area from less than 1 to 1,300 m² (Halua pond, Group E), most of them being very small. Similarly, total water surface area of a group ranges from a few square meters (e.g., Group C) to more than 2,000 m² (Group F). Relative surface areas are indicated by circle size in fig. 1. Most pools are less than 0.5 m deep, but Halua Pond exceeds 5 m in depth. Surface areas and depths vary considerably with tide level, many of the shallower pools temporarily decanting at low tide.

Pools within a group tend to have similar basin structure (table I). Rock basins consist of rubble or larger segments of lava without noticeable epilithic

TABLE I.

Anchialine pool groups of Cape Kinau, Maui (cf. fig. 1): letter coding used here and by other authors, pool basin character, sampling effort, and temperature and salinity ranges[1].

Pool group				Number sampled[2])		Temperature °C	Salinity ‰
This paper	Holthuis 1973	Wong 1975	Basin type	Dates	Pools	Min. - Max.	Min. - Max.
A	a,b,c,d	O,P	rock	7	8	21.0 - 28.5	10 - 34
B	h,i,j	N	rock + crust	3	5	23.0 - 25.0	10 - 17
C	k	M	rock	2	1	23.0 - 25.0	8 - 17
D	e,l	K,L	rock + crust	6	3	22.5 - 26.0	6 - 18
E	m,n	J	sediment	19	1(1 m) (2 m)	20.5 - 28.0 23.5 - 29.0	9 - 20 12 - 31
F	o,p	I	sediment	19	6	21.0 - 30.5	6 - 25
G	r,s	F	rock + crust	13	3	22.0 - 25.0	7 - 24
II	q	G,II	rock	9	1	23.0 - 25.5	7 - 21
I	f	E	rock	12	3	21.0 - 26.5	12 - 34
J	w,x	D	sediment	13	2	20.0 - 27.0	7 - 19
K	u	B	sediment	10	1	20.5 - 26.5	6 - 16
L	t	A	sediment	12	1	21.0 - 26.0	7 - 17

1) Mid-depth values except 1 and 2 m depths in pool, Group E.
2) Selected pools in each group were sampled irregularly during the year, October 1971 — September 1972, once on any given date except as noted in the text.

coating. Rock + crust refers to rock coated with a biogenic crust (see Flora below) and usually with minor amounts of sediment. Sediment basins are thick deposits of unconsolidated mineral particles with organic debris, and are generally bordered by crusts. Exceptions in basin structure conformity occur within some pool groups, especially in Groups E, F, J, and L which have a few rock or rock + crust pools associated with predominantly sediment basins. Pool waters are characteristically clear although temporary planktonic turbidity was observed in a few of them. Halua Pond (Group E) has continuous turbidity in the surface layer (1 m) as well as an accumulation of particles in a sharp pycnocline.

The nature of pool water is spatially and temporally complex as a result of

variable mixing of source waters: the intruding seawater with its daily tidal effects, and the cooler, seaward-percolating, fresh groundwater. Dissolved oxygen, temperature, and salinity were measured in one or more pools within each group at irregular intervals during the period October, 1971 to September, 1972. Oxygen was measured electrometrically, temperature with resistance and mercurial thermometers, and salinity refractometrically. Shallow pools (< 0.5 m) were sampled at mid-depth; in deeper waters, subsurface and bottom measurements were made. On two occasions, diel observations were made at hourly intervals in one pool in each of Groups E and F. Salinity was also estimated occasionally in the vicinity of observed shrimps.

Oxygen levels generally were within 20% of saturation values for the ambient temperature and salinity. In the presence of abundant vegetation, however, a daily cycle of midday supersaturation (approaching 200%) to predawn subsaturation (to about 30%) was observed. This response to photosynthesis and respiration was especially evident in certain pools of Groups E, F, and J. The oxygen fluctuation did not appear to affect the distribution of motile fauna such as shrimps.

Water temperatures and salinities are summarized in table I as ranges observed within each pool group over the entire survey period. All pool groups considered, anchialine waters of Cape Kinau ranged from 20 to 30.5°C, and 6 to 34‰. Temperatures varied least (2-3°C) in Groups B, C, and G, and most (9.5°C) in Group 1. Salinity variation was low in Groups B (7‰) and K-L (10‰), and highest in Group A (24‰). Although only selected pools within a group were sampled repetitively, total variation within one group (F) was estimated by sampling 24 pools during a 2-hr period on 24 October 1971: bottom water temperatures ranged from 24 to 30°C and salinities from 9 to 20‰.

A comparison of long- and short-term variation at a single sampling point was provided by measurements made at the bottom of one pool in Group F:

Duration of sampling	*Temperature*	*Salinity*
One year, 19 dates	22.0 - 28.0°C	8.0 - 22.0‰
One day, hourly intervals	23.0 - 28.0°C	13.5 - 21.0‰

During the diel measurements, water depth at the sampling point varied from 0.4 to 0.75 m. Temperature extremes related to the solar cycle (minimum at 0515 hrs, maximum at 1415 hrs) while salinity coincided with tidal extremes (minimum at low tide, 2200 hrs; maximum at high tide, 1000 hrs). Most of the variation of these factors in a given pool group as shown in table 1 can be attributed to daily fluctuations.

AQUATIC FLORA

The vegetation of Cape Kinau pools was studied extensively by Wong (1975). Information presented here summarizes the highlights of that study. Some

marsh-type riparian vegetation occurs around pools with sediment basins. Representative salt-tolerant plants include small rush (*Juncus* sp.), trailing forbs (e.g., *Sesuvium portulacastrum*), and low shrubs (e.g., *Batis maritima*). Their sparse growths, however, contribute little to pool ecology compared to the diverse, often lush assemblages of algae (> 140 spp.) and a prominent vascular plant, *Ruppia maritima*.

Algae are represented by 71 diatoms, 20 chlorophytes, 2 chrysophytes, 41 cyanophytes, 3 pyrrophytes, and 5 rhodophytes. Relatively few of these algae occur either as visually obvious growths or as the bulk of the plant biomass in a given pool. These prominent species and species complexes are identified in table II with their distributions by pool group. The more ubiquitous algae are *Hildenbrandtia* (*H. prototypus*), *Lyngbya* crusts, and *Scytonema* mats, each occurring in eight or more of the pool groups. *Hildenbrandtia* is a superficially amorphous rhodophyte most evident as a thin, dark red coating on rock surfaces. Crusts and mats are complex assemblages of various algae that are distinguishing features of many anchialine pools.

TABLE II.

Prominent components of the anchialine pool macroflora of Cape Kinau, Maui, and their distributions by pool group (cf. fig. 1, table I). Adapted from Wong, 1975.

Prominent pool flora	Occurrence by pool group												Number of pool groups
	A	B	C	D	E	F	G	H	I	J	K	L	
Algae													
Chlorophyta													
Enteromorpha spp.						x				x	x	x	4
Caulerpa spp.	x				x								2
Cladophora spp.	x					x					x	x	4
Cyanophyta													
Lyngbya crust		x		x	x	x	x	x	x	x	x	x	10
Scytonema mat		x		x	x	x	x			x	x	x	8
Rhodophyta													
Ahnfeltia concinna	x		x						x				3
Hildenbrandtia sp.	x	x	x	x		x	x	x	x		x		9
Lithophyllum sp.	x								x				2
Vascular plant													
Ruppia maritima						x				x	x	x	4

Crusts are tan or orange, often laminated, accretions of algae and carbonate particles that frequently form flat-topped banks around pools or coatings on submerged rocks. *Lyngbya mesotricha* is the principal algal component, but the assemblage includes other filamentous and coenocytic algae as well as diatoms. Mats are dark green or brown felt-like pads composed of various algae (as in crusts) but lacking mineral particles. The cyanophyte *Scytonema cincinnatum* is

the major algal component in most mats, but some are formed by *Lyngbya keutzingiana*.

Among other prominent algae *Ahnfeltia concinna*, *Caulerpa* spp., and *Lithophyllum lichenoides* are marine forms restricted to waters of continuously high salinity. The filamentous chlorophytes, *Cladophora* spp. and *Enteromorpha* spp. abound in a few pools, often in association with *Ruppia maritima*, a rooting phanerogam that requires basins with soft sediments.

FAUNA

Pool macrofauna is much less diverse than the algae, but like the flora, there are relatively few ubiquitous species. Species collected are listed below according to major taxa; pool groups in which they were found are indicated by letter coding (cf. table I, fig. 1).

Sponges
- *Tethya* (*T. diploderma*?): A,E,F,I
- Unidentified spp.: E,F

Hydrozoan
- *Cordylophora caspia*: E

Anthozoan
- *Actinia* sp.?: A,F,I

Polychaetes
- Capitellidae, unidentified sp.: E,F
- *Cirriformia semicincta*: F
- *Eurythoe camplanata*: A,E,F,I
- *Nereis jacksoni*: F
- *Salmacina dysteri*: F
- *Spirorbis* sp.: F

Snails
- *Assiminea nitida*: A,E,F,J,K,L
- *Bittium zebrum*: E
- *Caecum crystallinum*: E
- *Laemodonta bronni*: E
- *Melampus parvulus*: E,J,K
- *Theodoxus cariosus*: E,F,K
- *Thiara* (*T. granifera*?): E,F,J

Insects
- *Trichocorixa reticulata*: A,K,L
- Odonata, unidentified sp.: J
- Diptera, unidentified sp.: E

Crustaceans
- Isopods
  - *Gnoriosphaeroma rayi*: I
  - *Ligia hawaiensis*: D,E,F,J,L
  - Unidentified sp.: J
- Amphipods (Barnard, 1977)
  - *Hadzia lonomaka*: A (type locality)
  - *Maera* sp.: A
  - *Nuuanu amikai*: A
  - *Parhyale hawaiensis*: A,B,F.L
- Decapods
  - 12 spp. (see next section)

Tunicates
- *Herdmania* sp.: E
- unidentified spp.: E

Fishes
- *Asteropteryx semipunctatus*: E,K
- *Bathygobius fuscus*: E,K
- *Eleotris sandwicensis*: B.F,G,J,K
- *Cymnothorax* sp. (*G. hilonis*?): F,G
- *Kuhlia sandvicensis*: B,F,G,J,K

Except for decapod crustaceans treated in the following section, faunal survey was not exhaustive. Many of the species are invaders from the littoral marine environment and were found only in waters of continuously high salinity. Among the snails, *Assiminea*, *Theodoxus*, and *Thiara* [= Melania] are euryhaline species common to other coastal ecosystems such as salt marshes and estuaries. *Thiara* also is common in many Hawaiian streams. Two of the fishes, *Eleotris* and *Kuhlia* are Hawaiian endemics typically resident in estuaries

and lower reaches of streams. Fishes occurred as scattered individuals and were abundant only in one pool in each of Groups D and E, and in most pools of Group K. All amphipods appear to be hypogean species not found in surface waters other than anchialine pools. The two identified isopods are epigeal: *Ligia* is an amphibious supralittoral species commonly found elsewhere; *Gnoriosphaeroma* is aquatic and occurs in some streams. The unidentified isopod, a dull orange colored aquatic, was found only among lava rubble in one pool and may be a hypogean species.

It is somewhat surprising that anchialine pools have so few representatives of major taxa such as coelenterates, echinoderms, and mollusks that abound in diversity in immediately surrounding marine water. For example, Dr. E. Alison Kay (unpublished data) collected and identified mollusks from adjacent habitats on Cape Kinau. Progressing seaward, the number of species found in each habitat was:

anchialine pool — 5 spp.
restricted tidepool — 13 spp.
open tidepool — 45 spp.
shallow littoral water — 81 spp.

Variable salinity and restricted subsurface connection to the ocean probably are the major factors limiting the colonization of anchialine pools by marine organisms. Another peculiarity in faunal representation in these pools is that diversity at intermediate taxonomic levels is nearly as great as at the species level:

Major taxon	Number of species	genera	families
Polychaetes	5	5	4
Gastropods	7	7	6
Isopods	2	2	2
Amphipods	4	4	2
Fishes	5	5	4

DECAPOD CRUSTACEANS

Crustaceans are the most prominent and characteristic animal life of Cape Kinau pools. Although the aforementioned isopods and amphipods contribute to crustacean diversity, it is the Decapoda which have the most species and constitute the bulk of the animal biomass. Identified decapods are represented by grapsid crabs and caridean shrimps. The crabs, *Metopograpsus thukuhar* and *Sesarma obtusifrons*, are amphibious epigeal species commonly found in other coastal habitats. Because they move terrestrially, these crabs can be found in all pool groups although careful searching is usually required. There is also another crab, a small (<2 cm carapace width) pinkish- or coral-colored aquatic with slender chelae. It was observed on several occasions in cracks of

TABLE III.

Caridean shrimps in anchialine pools on Cape Kinau, Maui, their distributions by pool group (cf. fig. 1), and minimum salinities at which they were found (cf. table I). Names preceded by an asterisk (*) are hypogean species restricted to the anchialine habitat.

Caridean shrimps	Minimum salinity ‰	Occurrence by pool group												Number of pool groups
		A	B	C	D	E	F	G	H	I	J	K	L	
Alpheidae														
Alpheus gracilis	11									x				1
Alpheus lobidens	11				x	x		x		x	x			5
**Metabetaeus lohena*	6	x	x		x	x	x	x		x	x		x	9
Atydae														
**Antecaridina lauensis*	12	x			x									2
**Halocaridina rubra*	6	x	x	x	x	x	x	x	x	x	x		x	11
Hippolytidae														
**Calliasmata pholidota*	14	x					x			x				3
Palaemonidae														
Macrobrachium grandimanus	6	x	x		x	x	x	x	x	x	x			9
Palaemon debilis	6	x	x			x	x	x		x	x	x		8
Palaemonella burnsi	12				x			x		x				3
Procarididae														
**Procaris hawaiana*	10	x								x				2
Number of species		7	4	1	6	5	5	6	2	9	5	1	2	

submerged lava in pool Group I, but attempts to capture or photograph it were unsuccessful. That this crab could be a hypogean species is an intriguing possibility.

The ten species of shrimps identified and listed in table III represent five caridean families. The distribution indicated updates that given by Holthuis (1973) and includes the species of alpheids discussed by Banner & Banner (1974). No pool group contained all ten species, the average being 4-5 species per group, but Group I lacked only *Antecaridina*. *Halocaridina* was most ubiquitous (11 pool groups), followed by *Metabetaeus* and *Macrobrachium* (9 pool groups).

Distributions of these shrimps appears to be related primarily to salinity and secondarily to predation. At the upper end of the range, all shrimps except *Macrobrachium* appear to tolerate euhaline (> 30‰) water. Four shrimps were found at the lowest salinity (6‰) recorded: *Metabetaeus*, *Halocardina*, *Macrobrachium*, and *Palaemon*. All of them are known to tolerate even lower salinities elsewhere (Maciolek, 1983; Maciolek & Brock, 1974). The other six shrimps were found at salinities of 10‰ or higher. Of the six, only *Antecaridina* has been found elsewhere at lower salinities. In the few pools where fishes were abundant, only *Macrobrachium* and *Palaemon* were able to co-exist — an indication of shrimp susceptibility to piscine predation. Observed bird predation was minor, being limited to the shallow open pools in Group F.

The ten shrimps represent two ecological groups based on habitat requirements. Five of them (table III) are considered epigeal species, which although secretive and generally nocturnal, have no apparent requirement for deep interstitial water. Those species are common in other environments, such as estuaries (*Palaemon* and *Macrobrachium*) and inshore marine waters (alpheids). *Palaemonella* is an uncommon shrimp first described from Cape Kinau (Holthuis, 1973; type locality, Pool Group I), but later found in open coastal ponds on Hawaii Island (Maciolek & Brock, 1974).

Hypogean shrimps are of particular interest because their known occurrences in exposed water is limited to anchialine pools where they often appear in large numbers, probably because of the enhanced food base. Of the five hypogean species (table III), *Halocaridina*, *Metabetaeus* and *Procaris* are Hawaiian endemics. All three have been found elsewhere in Hawaii (Maciolek, 1983; Maciolek & Brock, 1974), but Pool Group A is the type locality of *Procaris* and also the place of first Hawaiian records for *Calliasmata* and *Antecaridina*. *Halocaridina* occurs in the greatest abundance (often in hundreds per m^2); *Procaris* and *Antecaridina* are the least common shrimps on Cape Kinau.

In addition to the identified shrimps discussed above, two other shrimps were observed in Pool Group I but never collected. Both were reddish in color, characteristic of hypogean species. One was of intermediate size (2-3 cm total length); it was seen only twice and observations were insufficient to even suggest a family affinity. The other shrimp was large (5 cm) and was seen on

several occasions. Field notes indicate a similarity in color, body form, and appendages to published descriptions and photographs of *Parhippolyte uveae* Borradaile 1899, a hypogean species recently removed from the genus *Ligur* by Manning & Hart (1984). Supporting this tentative identification is a 1981 collection record for *P. uveae* from a littoral marine cave located only a few kilometers from Cape Kinau (Maciolek, 1983).

AHIHI-KINAU NATURAL AREA RESERVE

In July 1973, Cape Kinau and peripheral marine waters to a depth of 20 m was formally established as Hawaii's first natural area reserve. Reserve boundaries encompass the entirety of the 1790 Kalua o lapa lava flow, including its undersea extension, and a portion of adjoining Ahihi Bay. Reserve status provides comprehensive protection of all natural values. Disturbance of any geological or biological features of the area is prohibited; observation and photography is encouraged. Collecting is allowed only by special permit issued by the State of Hawaii, Department of Land and Natural Resources.

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